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Damage identification of a full-scale five-girder bridge using time-series analysis of vibration data

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A B S T R A C T

This paper presents damage identification of a full-scale, five-girder bridge subjected to controlled levels of sequential damage using time-series analysis of vibration data measured during field tests and also simulated by finite-element (FE) modeling. Three-dimensional (3-D) FE models of the bridge corresponding to various damage scenarios considered for the experiment are constructed and calibrated using the modal parameters of the tested bridge extracted from vibration records obtained using a relatively dense measurement grid. A time series-based damage identification technique, autoregressive with exogenous input (ARX) models and sensor clustering, is evaluated using the real bridge data and the simulated bridge data obtained from the boundary value problem. Modification of the technique through incorporation of a new damage-sensitive feature (DSF) is proposed to enhance identification of the induced damage to this highly redundant bridge. The effects of damage locations, damage extents, and vibration measurement noise on the damage identification results of the bridge are investigated. The analysis results indicate that the damage identification technique can be successfully used to identify the existence of damage in this highly indeterminate bridge. It is found that damage location, damage extent, and vibration measurement noise significantly impact interpretation of the inferred damage location. The effects of interpretation parameters on the damage identification results are discussed in detail.

1. Introduction

In recent years, Structural Health Monitoring (SHM) [1] of bridges has received increasing attention from civil engineering researchers to identify the damage that may occur within the typical bridge life cycle. A majority of studies on this subject focus on developing vibration-based techniques that assess the dynamic property or response changes of a structure to identify damage. These vibration-based techniques are based on the premise that any physical property changes in a structure will alter the structure's dynamic characteristics, which can in turn be used to identify damage or deterioration in the structure [2,3]. Modal parameters such as natural frequencies and mode shapes have been frequently used as damage-sensitive features (DSFs) to identify damage [3–5]. For example, Magalhães et al. [5] used natural frequencies identified from bridge monitoring data as DSFs and analyzed their changes via control charts, one of the primary techniques of statistical process control, to detect damage.

Time series-based damage identification techniques are among the vibration-based damage-identification techniques commonly used by researchers for bridge SHM [6–8]. In time series-based damage identification techniques, dynamic response of a structure (displacement, velocity or acceleration) in healthy condition is calibrated with time series model(s) using model coefficients that minimize residual errors. These models are then compared for any unknown (damaged) condition to obtain its corresponding model coefficients or residual errors. Any significant changes in these coefficients or residual errors are considered to indicate damage in the structure.

Several different time series-based damage identification algorithms have been developed in the past to extract DSF that can identify damage in a structure [9–13]. Various DSFs, based on the technique used, have been proposed to detect the damage. For example, Lu and Gao [9] and Sohn and Farrar [10] used the standard deviation of residual error, which represents the difference between the measured signal and the predicted signal, as a DSF. More recently, Gul and Catbas [11,12] defined a "fit ratio" based on the norms of predicted output subtracted from measured output and measured output compared with its mean and used the

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difference between the fit ratios in healthy and damaged conditions as a DSF.

Vibration-based damage identification techniques are desirable for bridge SHM as damage can be detected through the use of a relatively small number of sensors that record bridge vibrations. However, application of vibration-based damage identification techniques to assess the structural integrity of real-life, full-scale bridges may pose significant challenges, such as the following: (1) local damage may not significantly alter overall (global) dynamic bridge characteristics [14,15]; (2) bridge dynamic properties are influenced by environmental changes [16–18], which affect bridge vibration response; and (3) measured actual bridge data are typically noise contaminated, often overwhelming small global response-based measurements [19]. New damage identification techniques, such as the one proposed in this study, need to address some of these challenges by developing measurement schemes that employ a large number of sensors and analytical approaches that can take advantage of a large amount of vibration responses obtained from a dense array of measurement points representing the state of bridge response to a simple excitation source, such as a drop-weight source.

This study presents the time series-based damage identification of a full-scale, five-girder bridge subjected to controlled levels of sequential damage using field measurements recorded by a dense array of geophones (highly sensitive sensors that record small-amplitude vibrations) and also using simulated vibration data obtained from calibrated finite-element (FE) models. The main objectives of the current study are to evaluate the efficacy of a time series-based damage identification technique on a highly redundant bridge with a high likelihood of load redistribution following subjection to a specified amount of localized damage and also to investigate the effects of damage location, damage extent, and vibration measurement noise on the bridge damage identification results. The bridge type selected for the current study is common in the state of Tennessee and throughout the United States in terms of span, connectivity, and structural details; therefore, the results obtained from this study apply to a large number of bridges.

Fig. 1. I-40 westbound bridge over 4th Avenue in Knoxville, TN.

2. Description of the test bridge

The I-40 westbound bridge over 4th Avenue, shown in Fig. 1, was a five-girder, three-span bridge constructed in 1967 in Knoxville, TN, and demolished during the I-40 expansion project, referred to as SmartFIX40 [14]. The 45° skewed bridge was 52.10 m long and consisted of three spans – 11.34 m, 27.28 m, and 13.48 m – as shown in Fig. 2. The bridge had a concrete deck supported by five steel girders, W36x135, spaced at 2.49 m intervals. Intermediate diaphragms were installed between the steel girders to increase bridge capacity against lateral loading. Before its replacement to accommodate additional lanes of traffic, this bridge was intentionally damaged by the second author's research group [14], working closely with the contractor, on an interior girder near a support, to provide the opportunity for collecting relevant data to evaluate the feasibility and efficacy of vibration-based damage identification techniques in cases involving highly redundant bridges in which damage is located on an interior girder, near a support, as previous studies using laboratory models have shown that vibration-based damage detection is less reliable for locating damage that occurs near a support [20].

The bridge was instrumented with inexpensive geophones (approximately $50 each), made by Mark Products (LRS-1000), to measure bridge vertical vibrations. The geophones were highly sensitive passive-velocity sensors that did not require additional amplification or conditioning, and therefore, they were chosen for the bridge SHM. The natural frequency, damping ratio, and

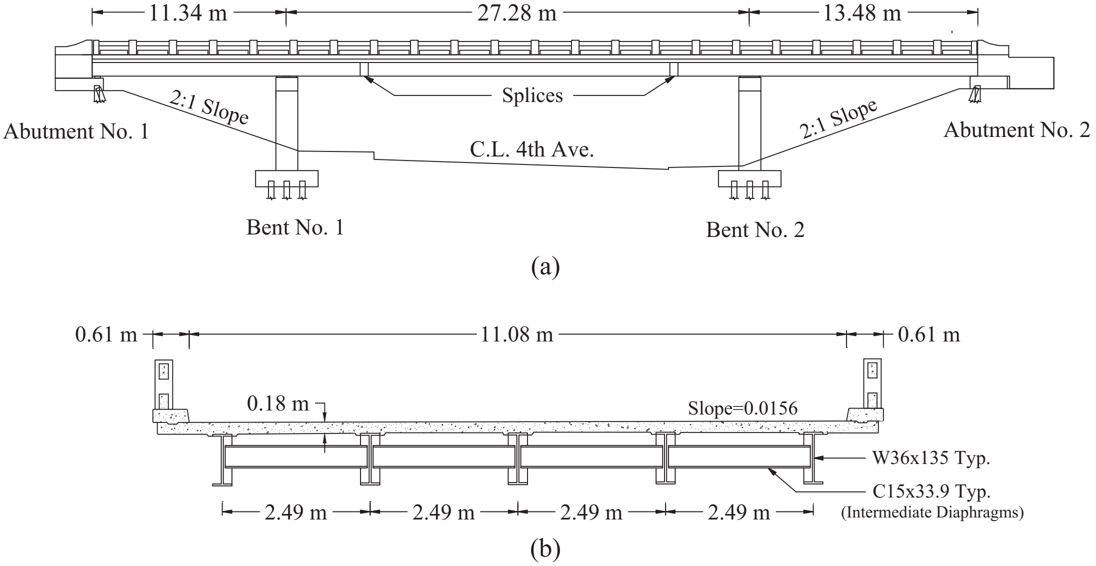

Fig. 2. I-40 westbound bridge over 4th Avenue: (a) longitudinal profile; (b) cross section.